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IMPROVEMENT OF SEABED CABLE PLOUGH TOW FORCE PREDICTION MODELS

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Abstract
As the use of offshore renewable energy sources such as wind and wave energy systems expands, they represent an increasing portion of the energy mix. Subsea cables connecting these resources are subject to many hazards, making cable burial using cable ploughing an important tool in preventing unplanned outages and downtime. This represents a significant installation cost for offshore renewables and there is a need to improve the accuracy of tow force, plough speed predictions and final burial depth of the cable. These are currently made using semi-empirical models as the large soil displacements involved cause instabilities in the finite element analysis. This paper provides an overview of work to develop new material point method numerical software to allow cable ploughing to be analysed and optimised. The focus of this paper is the physical modelling carried out to provide validation of the software, which includes both 1g and centrifuge testing, as well as considering interim ways to improve the existing semi-empirical models.

1. Introduction

1.1 Seabed ploughing

The expansion of energy production from renewable sources such as wind, tidal and subsea currents is presenting new challenges to industry. Foremost of these challenges is the need to improve the cost-efficiency of these sources. This is even more vital given the fact that offshore renewables are expanding into new areas further from shore, which present greater technical challenges to cost-effective installation than those areas used to date.

The difficult environment means that offshore energy is more expensive per unit of energy than both onshore renewables and fossil fuels, and a not insignificant portion of the overall installation costs for renewables is due to cabling costs. As an example, the UK Renewables Advisory Board (2010) estimates that cabling costs account for 9% of the total installation costs for offshore wind turbines. There are currently uncertainties surrounding the cable installation process that present the opportunity to improve its efficiency.

There are a number of hazards which pose a risk to subsea cables such as damage due to ship anchors or from seabed trawling (Ivanovic et al, 2011). Additionally, in colder waters iceberg scour presents an additional risk (Arnau and Ivanovic, 2015). Due to the inaccessibility of the cable and the time required for repairs, these hazards can lead to extended periods of time where offshore renewable infrastructure may be offline.

To overcome these issues, subsea power cables are buried to depths of up to 3 metres using seabed ploughing. This technique has been used extensively by the oil and gas industry to protect subsea pipelines, which have diameters of up to 1.5 metres, and has been widely researched (e.g. Lauder et al, 2012; Lauder et al, 2013). The process involves using a sea-bed pipeline plough to create a v-shaped trench into which the pipeline is placed, before being infilled by a backfill plough.

However, subsea cables differ significantly from pipelines, and have a markedly smaller diameter of around 200mm (BERR, 2008). This requires a different installation method, and instead a cable plough may be used to cut a narrow vertical trench into which the cable is placed. Once the plough has passed, the trench may collapse onto the cable meaning that no backfilling is necessary. The varying installation methods and significant variation in equipment geometry means that previous research on pipeline ploughing cannot be easily applied to cable ploughing and hence there is a need for further research to improve the understanding of the process. To ensure that cabling projects can be completed on schedule and avoid financial penalties, it is necessary to have accurate predictions of the plough performance, including tow force, depth, stability and speed for the specific seabed soil conditions.

The current technique used to predict the performance of cable ploughs is semi-empirical, and involves back analysis of the specific plough design in question from real ploughing telemetry to determine the model parameters to be used (Cathie, 2001). However, just obtaining accurate seabed characterisation data in offshore conditions such as the soil state and material properties (where there may be large distances between points of intrusive characterisation) is problematic, which raises questions over the data against which semi-empirical models are calibrated. Theoretical models for plough behaviour do exist, but their complexity and further uncertainties surrounding parameter selection mean that they are not widely used in industry (Beindorff et al, 2012). Additionally, these techniques are not useful when attempting to optimise new plough designs or geometry for which there is not yet any calibration data or to predict plough response in soil conditions that have not previously been experienced. Normally, geotechnical finite element analysis (FEA) may be used in an attempt to overcome issues such as these, however, the applicability of FEA to seabed ploughing is limited by mesh distortions which occur at large displacements, leading to instabilities in the analysis (Peng and Bransby, 2011).

1.2 Project overview

The aim of this project is to overcome these challenges by developing a numerical analysis software based on the material point method (MPM) able to model seabed ploughing and other soil-tool interaction problems (Wang et al, 2017). The use of the MPM avoids the mesh distortions associated with conventional FEA and allows the modelling of large deformation problems. This software will allow rapid analysis of the impact of varying share geometries on plough performance, allowing optimisation of future plough designs. Another benefit is that it will be possible to predict plough response in challenging soil conditions. A more detailed description of the MPM software development is given by Cortis et al (2017).

The project is being carried out jointly between Durham University, where the software is being created, and the University of Dundee, where

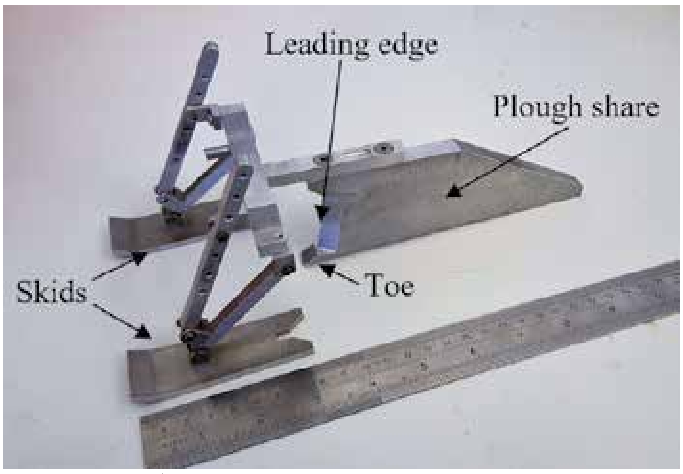

Figure 1: 1/50th scale seabed cable plough

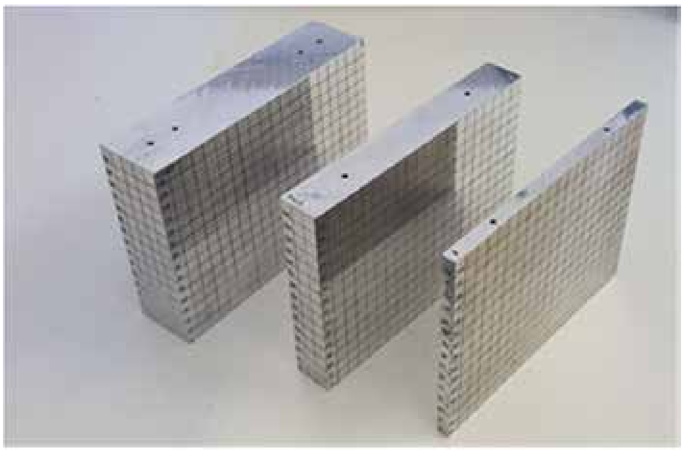

Figure 2: Simplified cable plough share analogue geometries (150 mm high x 200 mm long)

physical modelling is being carried out to provide verification data that will be used to benchmark and validate the software. This paper will focus on small scale model testing carried out at the University of Dundee using simplified analogues of cable ploughs which are easier to model using the numerical software.

In addition to the work described here, the University of Dundee is also undertaking 1g tests using 1/50th scale models of both cable ploughs and pipeline ploughs in order to provide validation of the final software against realistic plough geometries and provide further confidence in the predictions. Additional work is also being carried out using the University of Dundee's 3 m radius beam centrifuge at an enhanced gravity of 50 g in order to investigate the scaling of 1 g model tests up to prototype scale (Lauder and Brown, 2014; Robinson et al, 2016).

Whilst the data gathered in the project is primarily for verification of the numerical software, it is also being used to improve both the understanding of seabed plough behaviour and current empirical models.

2. Methodology

2.1 Idealised plough share geometries

The numerical modelling of cable ploughs is complicated by several aspects of their geometry such as the angled leading edge and the 'toe' at the base of the share (Figure 1). Whilst important for the stability and efficiency of the plough in the field, these may be problematic to model numerically. To overcome these issues, the plough shares were idealised as simple rectangular blocks (Figure 2) which were constrained vertically to keep the embedment depth constant and ensure their stability. This simplification also allows the individual forces acting on each aspect of the share to be deconvoluted and identified. To ensure consistency between the various geometries, the blocks were manufactured from aluminium and given a polished surface finish to maintain a consistent low interface friction ratio.

2.2 Experimental setup

Three parameters were varied in the experimental programme to enable their impact on tow forces to be identified; embedment depth, share width and sand density (Table 1). The properties of Hostun 95 sand (CN HST95) which is the evenly graded fine sand used throughout the testing are summarised in Table 2. The tests were conducted in a 2.4 m long ploughing tank to ensure that the plough geometries are displaced sufficiently to achieve steady state (Figure 3). To provide actuation, a high torque DC motor with a variable speed controller was used to move a platform mounted on low friction linear bearings attached to the tank. Linear displacement measurement was by means of a draw wire transducer (DWT) connected to the rear of the platform.

Table 1: Ranges of parameters used in physical modelling

Test variables	Sand relative density (%)	Share embedment depth (mm)	Share width (mm)
Range of parameters used	30 50 70	20 50 80	10 30 50

Table 2: Properties of HST95 sand (Lauder et al, 2013)

Property	Value
One dimensional Young's modulus, E'_0* (kN/m^2)	647
Maximum dry density, ρ_{max} (kg/m^3)	1792
Minimum dry density, ρ_{min} (kg/m^3)	1487
Mean grain diameter, d_{50} (mm)	0.13
Critical state friction angle, $\varphi'_{crit}{}^{\#}$ (°)	32
Critical state interface friction angle, $\delta'_{crit}{}^{\#+}$ (°)	18

* E'_0 determined at an effective stress of 0.2 kN/m^2 and at a relative density of 53 %.
\# Friction angles determined at normal stresses of 0.2-70 kN/m^2.
\+ From tests for this project, not based on Lauder et al (2013).

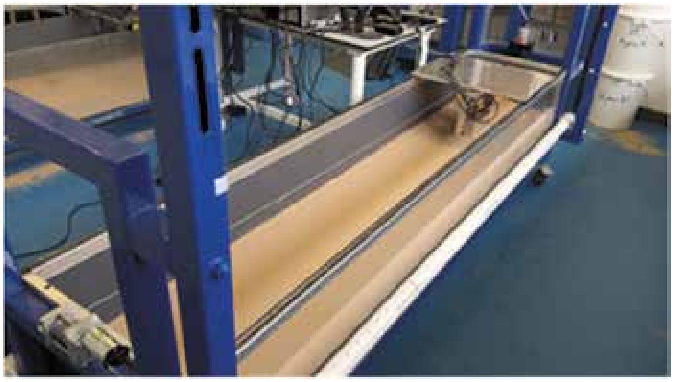

Figure 3: Ploughing tank before test commences

Figure 4: Load measurement frame

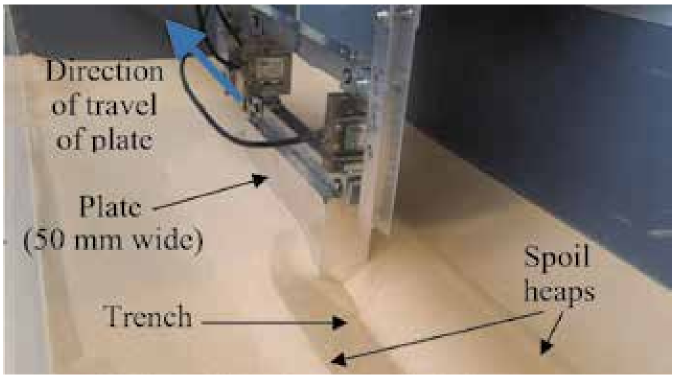

Figure 5: Model ploughing test after completion

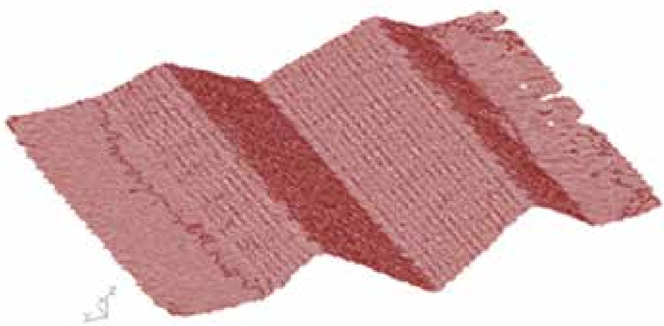

Figure 6: 3D scan of final physical model surface

The load frame to which the plough share geometries were attached consisted of three load cells which allowed the total vertical and horizontal forces acting on the share to be measured. Figure 4 shows the load frame which constrains the share geometries, consisting of two 20 kg vertical load cells located at the front and rear of the plough and a third 20 kg load cell at the front of the share for measuring horizontal forces. The plough share geometries attach to the load frame via a detachable bar to allow the geometries to be left in place after the test, preserving the final soil surface geometry for 3D scanning. The load cells are connected to the frame by pinned connections fitted with dust resistant low friction rotational bearings to minimise any moment transfer.

Data logging for the load cells and the DWT were provided by a National Instruments NI DAQ 6211 logging system. Additionally, the surface of the sand bed was captured after ploughing using a low cost 3D scanning system to allow the final surface deformations and trench profiles to be compared with the output from the numerical model (Figures 5 and 6). The system can capture the soil surface to an accuracy of ±0.5 mm, and provides output in an easy to interrogate 3D model. The simple low cost scanning system and its use are described in more detail by Robinson et al (2016).

2.3 Test procedure

The sand beds were prepared by dry pluviation using a linear slot pluviator, and the different densities were achieved by varying the slot width to alter the sand fall rate. The pluviator was moved repeatedly across the ploughing tank at a rate of 150 mm/sec until the required sand bed depth of 200 mm was achieved. Densities were confirmed by three density measurement pots placed within the ploughing tank. The plough share was then embedded to the required depth and attached to the platform. The draw-wire transducer was then connected to the platform and a displacement of 1500 mm was applied at a rate of 5 mm/sec whilst logging the various transducers.

After the test was complete, the plough share was disconnected from the load frame which was removed along with the platform, leaving the plough share embedded within the sand bed. This allowed the final undisturbed soil surface to be captured using the 3D scanner.

3. Results and discussion

3.1 Tow forces

Figure 7 shows the horizontal tow force along with the overall vertical force from the two vertical load cells against the horizontal share displacement. The data shown relates to a 50mm wide idealised share geometry, embedded to a depth of 80mm. As with all of the tests discussed in this paper, the test was conducted in medium dense HST95 sand with a relative density, D_r, of 50%. The section of the data that is of most interest is the steady state, where the forces acting on the share have reached equilibrium. As shown, both the vertical and horizontal forces reach this rapidly, typically after only 300mm out of the total 1500mm displacement applied. Despite the fact that the steady state has been reached, oscillations can still be clearly seen. These are related to the mechanism by which the soil fails around the plough as it displaces. As a failure mechanism starts to develop, the soil shear resistance rises until the peak resistance is reached. As the displacement continues, the resistance reduces to the critical state, before the mechanism ceases to be viable leading to the formation of a new failure mechanism and the process repeats. Similar mechanisms were noted for plane strain testing of pipeline plough analogues by Lauder (2010).

Prediction of tow forces is a key factor prior to embarking on field operations as this determines the required bollard pull, rate of progress and influences the selection of the vessel to be used for installation. These tow forces may be predicted using the semi-empirical model by Cathie (2001) which is shown in Equation 1.

$$F_{cable} = F_w + C_s\gamma D^2 + C_d v(C_s\gamma D^2) \qquad (1)$$

Where:

C_s and C_d are empirical coefficients
γ is the soil unit weight
D is the plough share depth
v is the plough velocity

As shown, there are three key elements in the model, each representing the impact of a different variable on the tow force. The tow force due to the plough self-weight, F_w, is constant regardless of the plough depth and is instead a function of the plough self-weight and

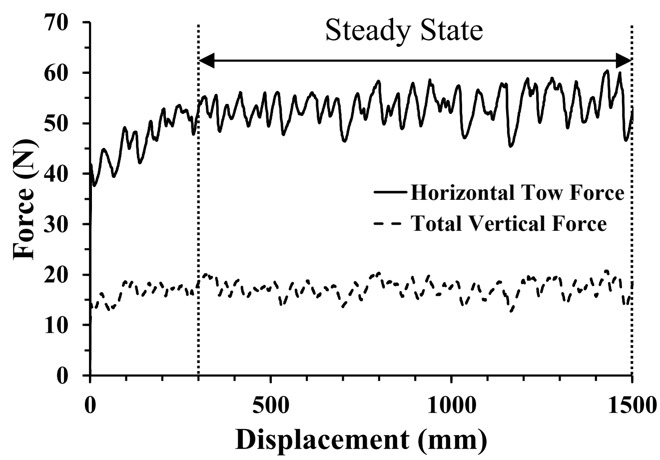

Figure 7: Typical horizontal and vertical forces (50mm wide share, 80mm embedment depth and 50% relative density)

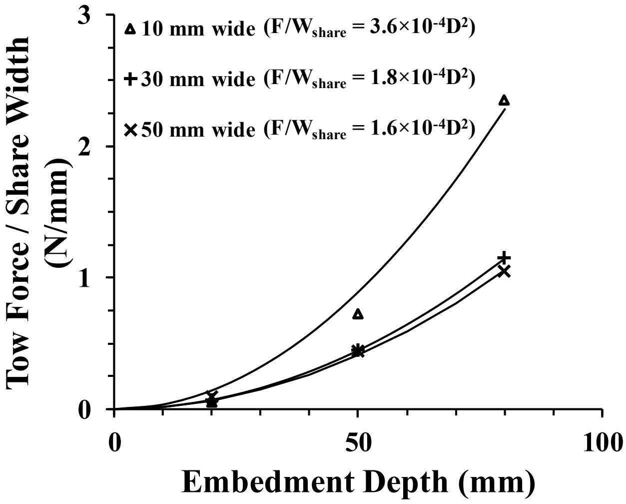

Figure 8: Tow force per unit share width against depth for varying share widths in medium dense sand

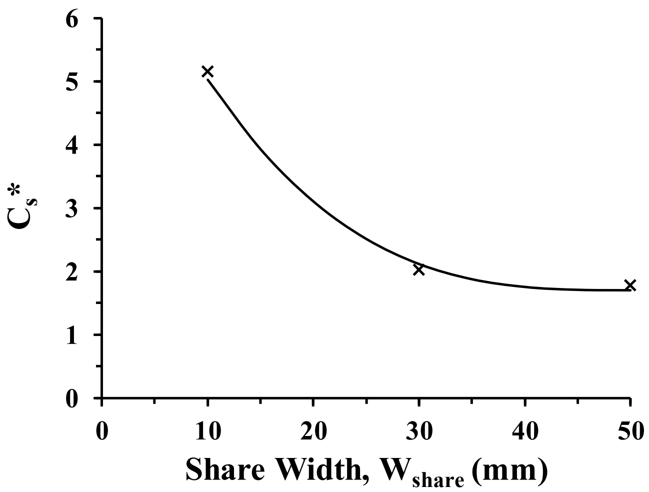

Figure 9: Variation of C_s* with share width at D_r = 50 %

the interface friction ratio of the plough-soil interface. The term involving C_s accounts for the tow force caused by the static or passive soil resistance that excludes rate effects, which are dealt with separately by the term involving C_d. This dynamic or rate effect component causes additional tow forces related to the velocity of the plough and are due to the fact that when saturated soil is sheared, dilation can occur, generating negative pore pressures which increase the soil's effective stress. In sands this dynamic component can be significant (Lauder et al, 2013), making rate effects in cable ploughing an important area for future research.

In the work discussed here, the simplified shares are connected to a load cell arrangement which carries any self-weight forces, meaning that F_w is negligible. Similarly, as dry sand was used, no rate effects occur. As F_w and C_d are zero, Equation 1 can be simplified to Equation 2.

$$F_{s,\ cable} = C_s \gamma D^2 \tag{2}$$

The variation of tow force (normalised by share width) with depth for three simplified plough share geometries with varying widths is shown in Figure 8. As required by Equation 2, a D^2 relationship has been applied to each share width using least mean square regression. The D^2 relationships were able to provide a good fit to the measured data points, validating the form of the model proposed by Cathie (2001) and indicating that the current model can accurately capture the impact of depth on tow forces. However, share width is a variable which, in comparison to depth, has not been extensively researched and Figure 8 also highlights that the model proposed by Cathie (2001) does not directly or separately account for the impact of share width on tow forces.

A new model is proposed (Equation 3) to replace the C_s term in Equation 1. This is based on other lateral loading applications such as retaining wall theory and lateral pile loading (Randolph and Gourvenec, 2011). This adds three new components to the model; the share width, W, the passive earth pressure coefficient, K_p, and a shaping coefficient, C_s*. Adding the width into the model has the benefit of making the formula dimensionless and allows K_p (Equation 4) to be used to estimate the expected force acting on the area of the face of the plough in a similar manner to a retaining wall. The function of the shaping factor, C_s*, is to account for the fact that the failure mechanism induced in the soil may be wider than the share width, similar to the behaviour expected in lateral pile loading.

$$F_{s,\ cable} = 0.5 C_s^* K_p^2 \gamma W D^2 \tag{3}$$

Where:

C_s* is an empirical coefficient
K_p is the passive pressure coefficient (Equation 4)
γ is the soil unit weight
W is the share width
D is the plough share depth

$$K_p = \frac{1+\sin\phi}{1-\sin\phi} \tag{4}$$

Using Equation 3, values for C_s* have been determined based on the data shown in Figure 8 (where γ = 16.84 kN/m^3). Figure 9 shows the variation of C_s* with share width, W_{share}, for the three geometries. This clearly shows C_s* reducing with share width, reaching a value of 1.8 for a width of 50 mm. This is as expected due to the fact that as the share width increases, effects due to the failure mechanism being wider than the share become less significant. A value of 1 for C_s* would indicate that the tow force is correctly predicted based on the passive earth pressure coefficient, however, the relationship in Figure 9 tends to a value of around 1.8 at the largest share width tested. This is most likely due to additional components of resistance on the plough such as interface friction on the plough sides which may require to be accounted for (Arnau and Ivanovic, 2015). This highlights that share width is a key variable which is not yet accounted for in the model proposed by Cathie (2001) and presents an opportunity for its improvement; one of the aims of this project.

3.2 Scaling considerations

While the results discussed in this paper are all at model scale, the implications of this testing may also be of interest at prototype scale. The geometries considered in this paper are simplified, however, based on their length they could be considered to have a scale ratio, N, of 40 in comparison to a real prototype scale cable plough. The scaling factors by which the main parameters reduce from prototype scale to model scale are shown in Table 3.

The sand particle size is not scaled as provided there are a sufficient number of particles in contact with the model surface the soil can be considered as a continuum and no grain size effects are observed. A number of studies have investigated this issue (Balachowski, 2007, Garnier et al, 2007) and it has been found that provided the ratio of model width to median sand grain diameter, B/d_{50}, is greater than 50 then grain size effects are negligible. For the testing discussed in this paper, the minimum value of B/d_{50} used was 77 (for the 10mm wide plough share) meaning that the soil can be considered as a continuum.

3.3 Trench geometry and soil surface profiles

Whilst the final trench geometries from the physical modelling are primarily for validation of the numerical software, trench profiles are also of interest to industry. Cross sections of the final trench profiles have been extracted from the 3D scans using CAD software, and are shown in Figure 10. As can be seen, the trench profiles vary significantly with the share width, providing a good range of surface profiles for comparison with the numerical software being developed.

Another advantage of the 3D scan data is that it allows measurement of the areas and volumes of the various sections of the trench (Table 4). This enables the overall volume change during ploughing to be estimated. Given the fact that dilation is an important aspect of soil behaviour during ploughing, this will provide valuable information for verifying the numerical software and confirming the suitability of the constitutive soil model used.

Table 3: Scaling factors for 1g model testing

Parameter	Scaling factor
Length	$1/N$
Volume	$1/N^3$
Mass	$1/N^3$
Stress	$1/N$
Force	$1/N^3$
Length	$1/N$

Table 4: Areas for each section of the surface profile at 1000mm displacement and net volume change of the cross section (80mm embedment depth, 50% relative density)

Plate width (mm)	Trench area (mm^2)	Spoil heap area (mm^2)	Volume change per unit displacement (mm^2)
10	-36.7	+345.8	+309.1
30	-462.2	+961.0	+498.8
50	-922.6	+1590.3	+667.7

4. Comparison with numerical analysis

In order to allow comparison with measured forces from the physical modelling, the reaction forces will be extracted from the numerical models. This will allow any variation in the measured horizontal and

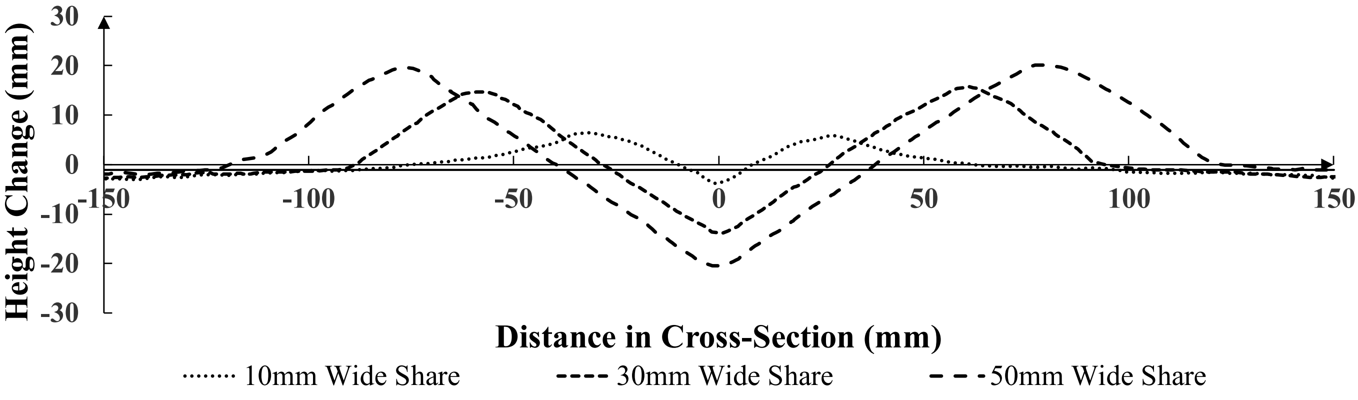

Figure 10: Cross sections for varying plate widths at an embedment depth of 80mm extracted from 3D soil surface scans

vertical forces to be identified and facilitate refinement of the numerical software.

Importantly, the 3D scanned surfaces can be used to validate the surface deformations predicted by numerical analysis of the physical models. One way this can be done is by comparing the key geometrical properties of the trench cross section such as the spoil heap height, trench depth and angle of repose. The cross sections can either be created using AutoCAD as described previously, or alternatively by using numerical visualisation software such as ParaView. ParaView also allows quantitative estimates of error in the numerical software to be obtained by directly overlaying both data sets and automatically computing the differences in elevation and volume.

5. Conclusions and future work

Cable ploughing is a vital process for providing protection to subsea cables connecting offshore renewable infrastructure, but which also contributes significantly to the cost of offshore renewable installation. Currently, cable plough performance predictions are made using semi-empirical models and there is a need to improve understanding of how cable plough share geometries contribute to resistance as well as more accurate techniques for predicting plough response.

The new material point method software being developed as part of this project aims to overcome these issues. It will facilitate plough design optimisation as well as the investigation of plough response in a wide range of seabed conditions, resulting in improved efficiency. Validation of the software is by means of extensive physical modelling carried out at the University of Dundee, which is also providing insight into the influence of share geometry on plough response and resistance.

Whilst existing models are useful in predicting the impact of varying share depth on tow force, there is the potential to improve these models to allow the impact of other aspects of share geometry to be accounted for. By testing simplified share geometries, it has been shown that the most commonly used tow force model by Cathie (2001) does not directly account for variations in share width and that this may cause variations in the model parameters. An alternative design equation, based more explicitly on passive resistance has been proposed and is seen to be capable of representing the model test behaviour. Future work as part of this project will investigate how this can be incorporated within the model. In addition, the project will investigate the impact of different leading-edge geometries on the plough tow forces, as well as validating the scaling of cable plough performance using further centrifuge testing.

The investigation of rate effects in cable ploughing will also be a significant component of the research in the next stage of this project. Due to the fact that rate effects may be significant in sands (Lauder et al, 2013) the ability to predict the dynamic coefficient, C_d, is imperative to the accurate estimation of plough progress rates. To investigate this, a programme of both 1g and centrifuge testing of 1/50th scale model cable ploughs using fully saturated sand at a wide range of plough speeds will be carried out. This will enable the impact of varying share geometries, soil conditions and plough depths on the dynamic coefficient to be determined and provide further insights into cable plough behaviour at realistic plough speeds.

6. Acknowledgements

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